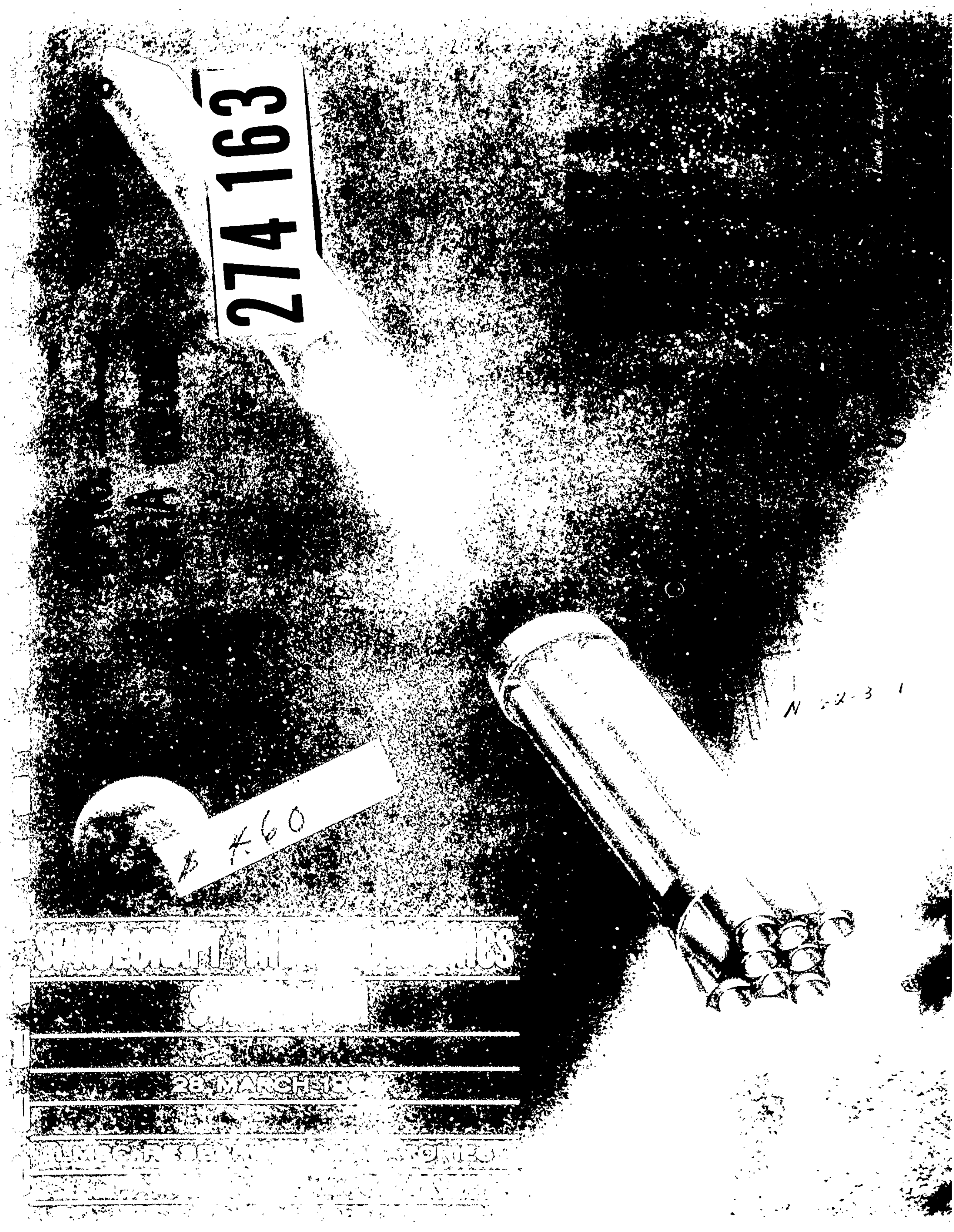
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Thermal and Atmospheric Control in Bioastronautic Systems

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The design and development of thermal and atmospheric control systems for spacecraft to orbit large primates is discussed. The evolution of design concepts, the analytical methods employed, and problems encountered during the development of such systems are summarized. Studies of systems suitable for manned spacecraft are discussed, with particular emphasis on the nearly closed regenerable-type system.

The purposes of this paper are to describe the design and development of thermal and atmospheric control systems suitable for sustaining a chimpanzee on orbit for varying periods of time; to discuss the differences between manned and animal systems; and to present the results of some LMSC studies related to manned systems, with particular emphasis on the nearly closed chemical regeneration system.

The chimpanzee systems are designated Bravo and Cocoa. The Bravo system is capable of sustaining a 50-lb animal in a closed environment for approximately 62 hr. The Cocoa system is being designed to sustain the animal in a closed environment for a significantly longer period.

SYSTEM REQUIREMENTS

The thermal and atmospheric control system must regulate the total pressure and gas composition, temperature, and velocity in an enclosure housing the animal (the life cell). In performing these functions, the system must supply oxygen for metabolism and leakage, and diluent gas for leakage (if a diluent is used). It must also remove carbon dioxide, water vapor, and as many trace contaminants as possible, and it must add or remove heat to maintain thermal equilibrium, within prescribed limits.

*The authors wish to acknowledge the efforts of R. S. Thomas and L. Washington in the preparation of material used in this paper.

Total Pressure and Oxygen Partial Pressure

The physiologic necessity for simulating a terrestrial atmosphere for space cabins has not been firmly established, although from a scientific viewpoint such an atmosphere provides the best basis for physiologic data. Available information indicates that various combinations of total pressure and oxygen partial pressure can be safely tolerated for indefinite periods.

Reference 1 indicates the allowable total pressure ranges for various oxygen concentrations in an oxygen-nitrogen mixture. With such a mixture, containing 21% oxygen by volume, the allowable total pressure range is approximately 8 to 40 psia for continuous exposure of unacclimatized subjects. Luft (Ref. 2) indicates that it is probably safe to assume that human subjects can function satisfactorily in a pure oxygen atmosphere at a pressure between 2 and 8 psia.

The low-pressure pure oxygen atmosphere eliminates the risk of aeroembolism, minimizes leakage, and simplifies the gas make-up system. However, considerations of system pressure drop, heat transfer, and fire hazard weigh heavily in the direction of a higher total pressure and the use of a diluent gas.

In the Bravo system, a pure oxygen atmosphere at 5 psia was chosen primarily because of the simplicity and availability of the single-gas makeup system.

In the Cocoa system, the necessary equipment to allow the use of a 14.7 psia total pressure oxygen-nitrogen mixture simulating air is being developed.

Temperature, Humidity, and Velocity

Human comfort depends on the dry bulb temperature, relative humidity, and gas velocity over the body; the degree of physical activity of the subject; the clothing worn; the insulation and radiation characteristics of the clothing, exposed skin, and surrounding

walls; and the mean temperature of the walls (Ref. 3). A detailed exposition on the relative effects of these variables is beyond the scope of this paper, but it may be said that the degree of comfort attained is the result of the net interchange of sensible and latent heat* between the subject and his environment. The heat loss over a sustained period must be neither more nor less than the rate of heat generation by the subject, and sweating (active secretion) should be at a minimum.

For the Bravo system, animal performance considerations led to a choice of an average life cell temperature of 80° F; a relative humidity of 50%; a gas velocity of approximately 30 ft/min; and an emissivity of 0.1 for the life cell walls. For the Cocoa system, however, the humidity control requirement was relaxed to allow the use of a simple condensation-separation water removal unit, and a somewhat lower gas velocity was allowed to save blower power.

Carbon Dioxide Partial Pressure

A recent review of the subject of CO_2 toxicity (Ref. 4) defines three levels of CO_2 concentration with respect to their effects on humans:

> 3% and above – performance deterioration and alterations in basic physiologic functions
>
> 0.5 to 3% – no change in performance or basic physiologic functions, but some physiological adaptation over a length of time
>
> Less than 0.5% – no adaptation

These are percentages by volume in air at sea-level pressure. The corresponding values of CO_2 partial pressure are 22.8, 3.8 to 22.8, and less than 3.8 mm Hg, respectively. The CO_2 partial pressure, rather than the percent by volume, is the critical factor (Ref. 5).

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*The term sensible heat refers to heat transferred to or from the body by convection, conduction, and radiation. The term latent heat refers to the heat absorbed in the vaporization of water on the surfaces of the skin and lungs.

Trace Contaminants

The concentrations of odorous gases which a chimpanzee can tolerate have not been determined. Aside from temporary odors, produced by the outgassing of materials when the atmospheric pressure is first reduced, odors in the life cell will emanate primarily from the occupant. It seems safe to assume that a chimpanzee is as capable of tolerating his own odors as a man; therefore an odor level tolerable to man was adopted as the design criterion.

Toxic gases considered in the design include intrinsic and extrinsic gases. The intrinsic gases are those which emanate from the animal and its excreta, such as carbon dioxide, methane, ammonia, and hydrogen sulfide. The extrinsic gases are those produced from materials in the life cell and the thermal and atmospheric control system. All internal materials, such as finishes, insulation, seals, and lubricants are evaluated prior to use with regard to the possible outgassing of toxic gases. The sealed cabin shuts out such potential external contaminants as unburned fuel vapors and exhaust products.

Oxygen Consumption

The rate at which the animal consumes O_2 depends upon his diet and physical activity. The relative amounts of carbohydrate, fat, and protein in his food determine the respiratory quotient, RQ , which is defined as the volume of CO_2 produced per unit volume of O_2 intake. For example, if 33.4% of the calories are supplied in the form of carbohydrates, and 66.6% supplied in the form of fats, an RQ of 0.80 results (Ref. 6).

The diet is also a determinant in the rate of oxygen consumption. With the 33.4% carbohydrate – 66.6% fat diet,the oxygen-to-heat ratio is 0.0165 lb/100 Btu (Ref. 6). The hourly rates of oxygen consumption may then be calculated from the expected metabolic rates. Asleep, the animal is expected to metabolize at 85% of his basal rate of 109 Btu/hr, or at 93 Btu/hr, and he will therefore require 0.015 lb/hr of oxygen. Active, at a maximum metabolism of four times his basal rate, he would generate 436 Btu/hr and therefore would require 0.072 lb/hr of oxygen.

The total amount of oxygen consumed by the animal during the mission depends upon his "activity profile." Requirements for the Bravo and Cocoa designs were based on a daily routine of 3 hr of maximum activity, 15 hr at the basal rate, and 6 hr of sleep. This results in an average heat generation of 146 Btu/hr and, therefore, in an average oxygen consumption requirement of 0.024 lb/hr. The metabolic oxygen requirement was increased by 50% to account for uncertainties in the activity profile, and allowances have been made to account for leakage.

Carbon Dioxide Production

Converted from volume to weight, an RQ of 0.80 corresponds to the production of 1.1 lb CO_2 per pound of oxygen consumed. The minimum CO_2 production rate, therefore, will be 0.017 lb/hr, and the maximum 0.079 lb/hr.

Water-Vapor Production

The rate at which the animal introduces water vapor into the atmosphere is determined from the rate at which heat is being absorbed by the vaporization of water on the lung and skin surfaces. The heat absorbed in this process is defined as the "latent heat loss."

Under zero heat storage conditions the latent heat loss is equal to the difference between sensible heat loss and total heat generation. Both sensible and total heat rates vary with animal activity and ambient temperatures. A simple digital computer routine has been devised to estimate the relationship between sensible and latent heat loss, and is described under "Analytical Methods."

The chemistry of reaction of CO_2 with lithium hydroxide shows that 0.41 lb of water is produced per pound of CO_2 absorbed. A portion of this water is vaporized into the gas stream and a portion retained in the absorber.

Heat Loads

In addition to the sensible and latent heat loads, there are internal heat loads arising from the heat equivalent of the power consumed by the blowers, internal control devices, cabin lights, psychomotor-task signal lights and controls, and the heat generated in the CO_2 and H_2O sorbers.

An external heat load on the life cell arises from conductive, convective, and radiative thermal interchange between the life cell, externally mounted equipment, and the recovery capsule. During the prelaunch, ascent, re-entry, and recovery phases of the mission, there is net heat transfer to the life cell; on orbit, there is net heat transfer from the life cell.

The design requirements for both the Bravo and Cocoa systems, based on these considerations, are summarized in Table 1.

ANALYTICAL METHODS

Considerable analysis is required to establish the requirements for the thermal and atmospheric control system, to evaluate preliminary system design concepts, and to predict system performance. Such analysis must consider the metabolic inputs and outputs associated with the primate, the chemical and thermodynamic processes taking place in various components, and the fluid flow and thermodynamic behavior of the entire system during all phases of the mission. Although it has been possible to modify existing LMSC digital computer programs (such as the Q-11 and Q-18 versions of the Thermal Analyzer) to perform the extensive numerical analyses required, programs specifically designed for the numerical analysis of a thermal and atmospheric control system would provide increased flexibility and efficiency.

The basic computing approach utilizes an n-dimensional, asymmetrical, finite-difference network where the problem is reduced to an analogous electrical circuit. This

Table 1

THERMAL AND ATMOSPHERIC CONTROL SYSTEM DESIGN REQUIREMENTS

Parameter	Bravo System	Cocoa System
Nominal atmosphere	Pure oxygen	$O_2 - N_2$
Total pressure (psia)	5.0 ± 0.5	14.7 ± 0.5
O_2 partial pressure (psia)	4.7 ± 0.6	3.1 ± 0.5
CO_2 partial pressure (mm Hg)	0 – 2.6	0 – 4.0
Trace contaminants	Below human tolerance	
Temperature (°F, dry bulb)	80 ± 5	80 ± 5
Relative humidity (%)	50 ± 10	Variable
Ventilation rate (ft/min)	30 – 50	15 – 25
Leakage rate (lb/hr)	0 – 0.012	0 – 0.034
O_2 supply rate (lb/hr)	0.015 – 0.084	0.015 – 0.080
CO_2 production rate (lb/hr)	0.017 – 0.080	0.017 – 0.080
H_2O production rate (lb/hr) (animal and CO_2 absorber)	0.050 – 0.315	0.050 – 0.307
N_2 supply rate (lb/hr)		0 – 0.026
Primate sensible heat load (Btu/hr)	46 – 141	46 – 141
Primate latent heat load (Btu/hr)	47 – 295	47 – 295
Equipment heat load (Btu/hr)	361 – 592	337 – 526
External heat load (Btu/hr)	-225 – 220	-150 – 250
Net heat load (Btu/hr)	229 – 1248	280 – 1212

approach may be used to solve any thermal problem whose finite-difference equation is analogous to the equation for a lumped-parameter RC electrical network. For example, the heat balance equation which is solved for the temperature at each node of the circuit at time $\theta + \Delta\theta$ is:

$$T_{\theta + \Delta\theta, i} = \frac{\Delta\theta}{C_i}\left(\sum_j \frac{T_{\theta, j}}{R_{ij}} + Q_i - T_{\theta, i} \sum_j \frac{1}{R_{ij}}\right) + T_{\theta, i}$$

where

$T_{\theta + \Delta\theta, i}$	=	the temperature at node i at time $\theta + \Delta\theta$
$T_{\theta, i}$	=	the temperature of node i at time θ
$\Delta\theta$	=	time increment
C_i	=	thermal capacity of node i
$\sum_j$	=	summation over all nodes connected by a resistor to node i
R_{ij}	=	the resistance between node i and any connected node j
Q_i	=	the heat rate into node i from sources other than conduction, convection, or radiation, from neighboring nodes

It is interesting to note how a program designed to perform this computation has been used to estimate the instantaneous latent heat loss from a primate. The routine described below has been developed for this purpose.

The sensible heat loss from the animal (who is represented in the thermal network as a single node) is programmed into the computer as a function of his surface temperature, which is computed in the same fashion as for any other node in the system. After a few iterations, the sensible loss is selected which provides a heat balance between the animal and his surroundings (life cell wall, atmosphere, couch, etc.). The sensible heat loss from the animal is transferred to an auxiliary circuit consisting of three nodes, connected by two resistances. The central node represents latent

heat loss and the remaining nodes represent the sensible heat loss and total heat generation. Total heat generation is programmed into the computer as a function of time. By proper selection of the two resistances, the auxiliary circuit is forced to perform a calculation which subtracts the animal's sensible heat loss from his total heat output, to obtain his latent heat loss. This latent heat loss is converted to a water production rate and then used by the program in further analysis of the system.

Other digital computer programs have been developed, based on the work of Camack and Edwards (Ref. 7), which calculate the incident heat fluxes from direct and reflected solar radiation, and from the earth, on surface elements of a satellite. The outputs of these programs can be fed directly into the Thermal Analyzer program.

Analysis of the thermal behavior of a payload when it is confined within a re-entry body, requires a careful treatment of the multitude of inter-reflections involved in the radiative heat transfer process. To aid in this task, a digital computer program has been developed at LMSC (Ref. 8), which calculates the constant K_{ij} in the equation $q_{ij} = K_{ij}\left(T_i^4 - T_j^4\right)$.

BRAVO SYSTEM DESIGN

An extensive preliminary design study preceded the Bravo hardware development phase. During this study, various approaches for meeting the system requirements were investigated. The following is a brief discussion of this investigation.

Oxygen Supply

Consideration was given to storage of the oxygen supply as a liquid, a gas, and in the form of chemical compounds such as potassium superoxide (KO_2) and sodium chlorate ($NaClO_3$). These supply methods are discussed in some detail below, and their major advantages and disadvantages compared in Table 2.

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and by loading at a pressure of approximately 900 psia, a moderate storage density is achieved. Heating is required to maintain a single phase in the reservoir as gas is withdrawn, which automatically maintains the necessary expulsion pressure. As with the cryogenic liquid storage system, an insulated container is required.

High pressure, ambient temperature. The simplest storage method uses high pressure to achieve moderate storage density at ambient temperatures. Reference 5 indicates an optimum storage pressure of approximately 7500 psia, at an ambient temperature of 95° F, if weight and volume are of equal importance. This storage method eliminates the requirements for tank insulation and temperature or pressure control.

Potassium superoxide. Potassium superoxide (KO_2) releases oxygen upon reacting with CO_2 and water vapor, and is effective in absorbing odors. This chemical* has been used in breathing apparatus for miners and fire-fighters. Reference 10 describes a demonstration of atmospheric control in a closed environment through the use of KO_2. When KO_2 is used to absorb all of the moisture and CO_2 produced by a man or animal, the amount of oxygen generated is greater than that required for metabolic consumption. It would be possible, however, to match the rate of oxygen generation to that required for metabolism and leakage through the use of supplemental CO_2 and/or water sorbents.

Some possible disadvantages with the KO_2 system arise from the complications associated with simultaneous control of the rates of oxygen generation, and CO_2 and water absorption, and from the danger of explosive decomposition catalyzed by organic materials.

Sodium chlorate. Sodium chlorate ($NaClO_3$) has found application as a solid chemical oxygen source (Ref. 11). The $NaClO_3$ is mixed with an inorganic binder, iron powder, and barium oxide, and cast or pressed into a cylindrical form.

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*Manufactured by Mine Safety Appliance Co.

The cast material has a density of approximately 150 lb/ft^3 and contains approximately 40% oxygen by weight. The equivalent oxygen density thus approaches that of liquid oxygen. Ignition can be performed at a spot enriched with iron using any one of several types of ignitors. The reaction is maintained by the heat of oxidation of the iron powder, and any free chlorine produced combines with the barium oxide.

Carbon Dioxide Removal

Controlled leakage, expendable and regenerable sorbent, and freeze-out systems were considered for removal of CO_2.

Controlled leakage. This method involves discharge of gas from the life cell at a rate sufficient to maintain the contaminant levels at or below desired values. The discharge rate required to maintain a CO_2 partial pressure of 2.6 mm Hg is also sufficient to maintain the water vapor partial pressure at a reasonable value. The large rate of oxygen loss required, about 80 times that needed for metabolic supply, results in an excessive weight penalty for this approach.

Expendable sorbents. Common processes for CO_2 removal are those of chemical absorption and physical adsorption. A number of solid materials are compared in Fig. 1 on the basis of theoretical* weight of sorbent required per pound of CO_2 removed, plus a weight penalty to account for the heat of reaction. For the purpose of comparison, this weight penalty was taken as the weight of water which would have to be evaporated to absorb the heat of reaction, per pound of CO_2 removed. On this basis, magnesium hydroxide and lithium hydroxide are very competitive. Lithium hydroxide (LiOH) has been used extensively as a CO_2 absorbent, one notable example being its use in the Project Mercury environmental control system. As a result, there exists considerable experimental data regarding the use of LiOH. Details of

*Under flow conditions, in a given application, the capacity of these materials will in general be less than that shown in Fig. 1.

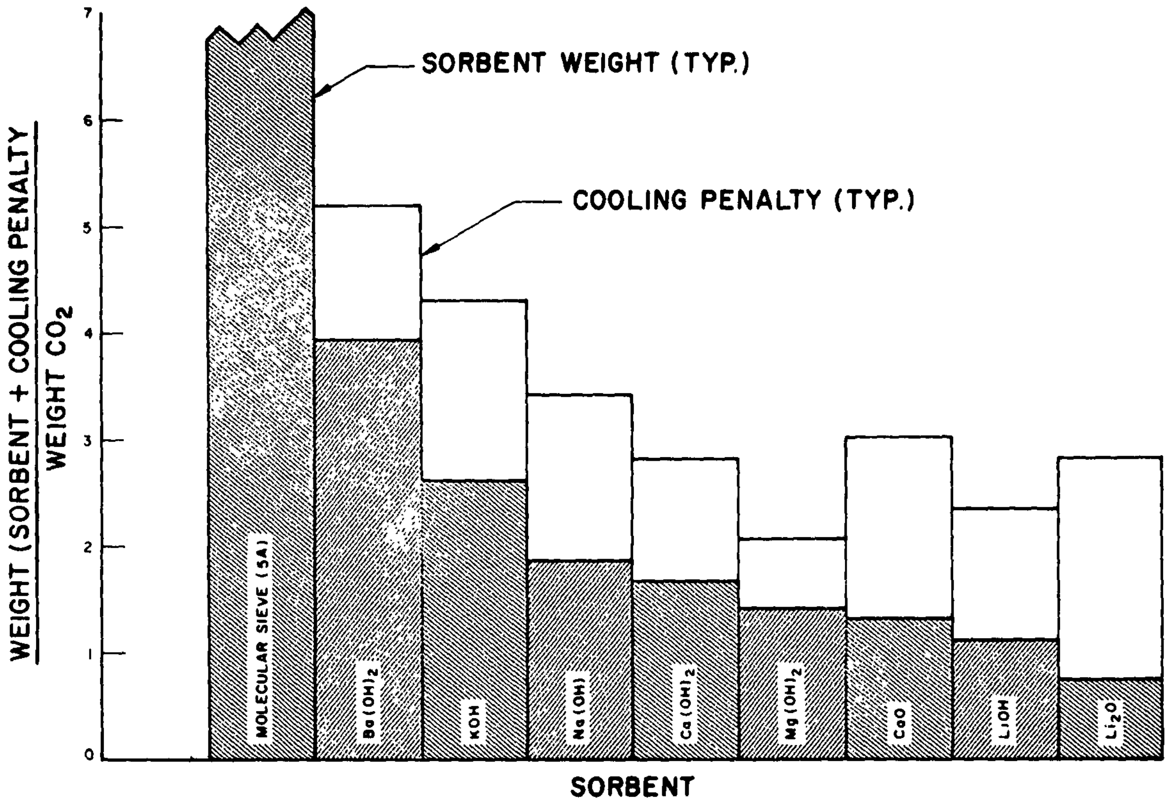

Fig. 1 Weight Penalty Comparison: CO_2 Sorbents

the design and testing of a LiOH canister for CO_2 removal are presented in Ref. 5. Although LiOH dust is very irritating, it is not toxic. By placing suitable filter media in the canister, dust can be prevented from entering the gas stream.

Regenerable sorbents. The alkali metal aluminosilicates, when used to adsorb CO_2, are readily desorbed by exposure to the vacuum of space. This material preferentially adsorbs water, and as a result the process gas must be extremely dry.

The design and development of a regenerable solid adsorbent system is treated in Ref. 12. Such a system, however, is more complex than the expendable sorbent system, and for the missions being considered it would not provide any weight advantage.

Freeze-out system. Systems wherein the CO_2 is removed from the gas stream by solidification at extremely low temperatures, using a "bootstrap" refrigeration system, appear attractive on a weight basis for medium duration missions (> 50 man hr) where the weight penalty for power is low (Ref. 12). The Bravo mission is equivalent to less than 50 man hr, and the weight penalty for power is sizeable. For these reasons, such a system was not considered for use.

Water Removal

Condensation-separation, and expendable sorbent systems were considered for water removal.

Condensation-separation. This method involves cooling the gas stream to a desired dew point, and collection of the moisture which is condensed in the process. The primary advantages of this system are the availability of the water for subsequent use, and essentially unlimited operating time. With such a system, however, special techniques are required to separate the condensate from the gas stream under zero-gravity conditions.

Expendable sorbents. Several expendable sorbents were considered. Magnesium perchlorate $Mg(ClO_4)_2$ appears attractive due to its high capacity for water [approximately 0.4 lb H_2O/lb $Mg(ClO_4)_2$] and moderate heat of reaction (approximately 545 Btu/lb H_2O). Difficulties arise in the design of an absorber column to utilize this material because the chemical deliquesces. A similar problem arises with lithium chloride.

Solid adsorbents such as the alkali metal aluminosilicates and silica gel maintain their physical strength and shape as they adsorb water; thus the flow distribution and pressure drop in a column packed with these materials is predictable and remains reasonably constant.

During the study, no adsorbents were discovered that have water capacities as high as that reported for $Mg(ClO_4)_2$. Of the adsorbents investigated, it was concluded that silica gel is superior for a low temperature application, and the alkali metal aluminosilicate for high temperature use. Figure 2 shows adsorption isobars, under equilibrium conditions, for these adsorbents. Data were obtained from the Linde Co. for the aluminosilicate (Molecular Sieve 5A), and from Ref. 13 for silica gel.

The average temperature of the water removal unit is expected to be in the range of 125 to 150°F. As a result, the aluminosilicate would be expected to exhibit a considerably higher capacity than the silica gel. Further investigation showed that the Molecular Sieve 13X* is superior to the Type 5A for water adsorption under the conditions encountered with this system.

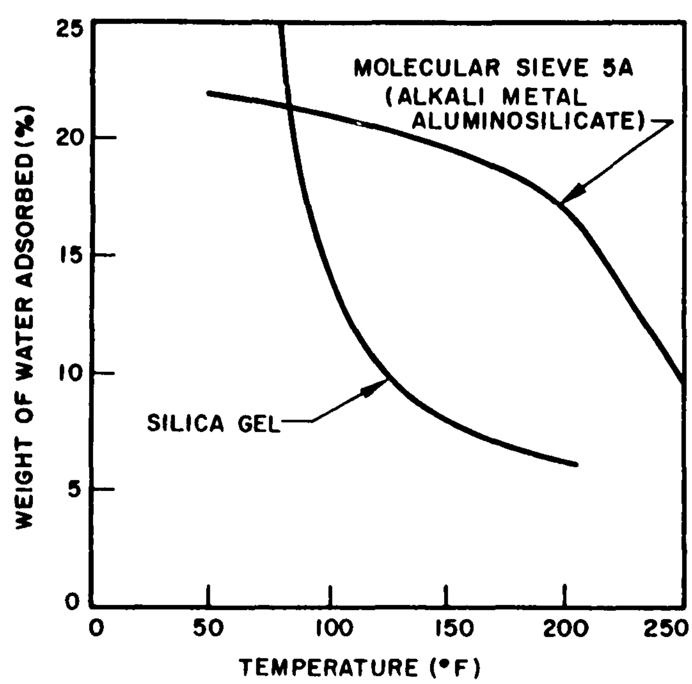

Fig. 2 Water Vapor Adsorption Isobars at 10 mm Hg Partial Pressure (Equilibrium Data)

*Manufactured by the Linde Company, Division of Union Carbide Corporation.

Trace Contaminant Removal

Activated carbon is extremely efficient in removing odors, and no alternate approaches were considered for this function. The problem of controlling the level of other trace contaminants is an important consideration. Through the careful selection of all materials which come in contact with the circulating gas, the rate of evolution of contaminants from these sources can be minimized. For missions of the duration being considered, this approach should be adequate to maintain trace contaminants well below threshold limits.

Thermal Control

Each phase of the mission imposes a different set of conditions on the thermal control system.

During the pre-launch period, significant external heat loads can arise from high-temperature ambient conditions and solar radiation, but a ground cooling unit can be used to remove the combined internal and external loads.

During ascent, the first few orbits, and re-entry, the recovery capsule average skin temperature exceeds the desired life cell temperature. During these periods the thermal capacity of the life cell can be used or the loads can be absorbed by other means such as the evaporation of an expendable coolant.

During the orbit phase, after the recovery capsule has cooled sufficiently, the external heat load becomes negative and the internal load can be rejected to the cold skin.

During ocean recovery, a positive external load arises, primarily from residual thermal energy in the recovery capsule skin. Under this condition, however, ambient air is cool enough to provide the necessary heat sink.

The thermal control problem was investigated in some detail for each of these mission phases. The results are discussed below.

Pre-launch, ascent, and re-entry. Analysis indicated that the thermal capacity of the life cell is inadequate to absorb the total internal and external heat load over the period required for the recovery capsule to cool, after being subjected to the ascent heating pulse. For this reason, an expendable cooling system is used during this period. The evaporator in this system is also used during the pre-launch period with Freon supplied from a ground source to serve as the evaporative coolant. The evaporative water system is also used during re-entry.

Orbit. The size of the expendable cooling system could be expanded to provide cooling through the entire mission, however, in keeping with one of the program objectives (to extend the state of the art) two thermal control systems were investigated which use space as the only heat sink. Both of these systems are based on the concept of varying the thermal resistance between the recovery capsule and the life cell to maintain reasonably constant life cell temperatures.

The first system used a series of low-emissivity radiation shutters interposed between the life cell and the recovery capsule. With the shutters closed, a maximum thermal resistance was established between the life cell and the recovery capsule, and with them open a minimum resistance was achieved. Provided that the range of this resistance is sufficiently great, steady-state thermal control can be achieved for the total range of internal heat loads and recovery capsule temperatures to be encountered. There are two primary problems with this approach: the weight and complexity of the shutter system and the use of the life cell wall as a heat exchanger. The latter results in wall temperature variations with internal load, and the necessity for a fairly high flowrate through the life cell to minimize the inlet-to-outlet temperature differential of the gas.

The second system employed a variable-flow fluid transport loop to vary the internal-to-external thermal resistance. Such a system requires a heat exchanger, mounted

in the circulating gas stream, a pump, a fluid bypass valve, and a set of radiators through which the fluid can pass. These radiators face the recovery capsule and are insulated from the life cell. When a maximum thermal resistance is desired between the life cell and recovery capsule, the fluid bypasses the radiators entirely and passes only through the heat exchanger and pump. When a minimum thermal resistance is desired, the full fluid flow passes through the heat exchanger and the radiators.

With this system, the life cell is well insulated from the recovery capsule, which allows the life cell wall and gas to approach equal temperatures. The gas flowrate through the life cell can be reduced from that required with the shutter system since the net heat transfer from inlet to outlet is reduced. The variable-flow fluid transport (radiant panel) system is also lighter and simpler than the radiation shutter system.

Recovery. For the ocean recovery period a simple ventilation system which draws ambient air through the life cell was the only approach considered. This ventilation system is opened during the parachute descent at an altitude of approximately 20,000 ft after internal and external pressures have been equalized. Under these conditions, a heater is used to maintain a life cell inlet temperature above 55°F.

System Description

In selecting the thermal and atmospheric control system for this application, reliability and availability were the primary considerations. As mentioned previously, one objective of the program was to extend the state of the art.

The selection of high-pressure gas for the O_2 supply, lithium hydroxide for CO_2 removal, and activated carbon for odor removal, allowed the use of previously developed and qualified hardware with a minimum of modification and for a small weight penalty. The use of a supercritical cryogenic O_2 supply and magnesium hydroxide as the CO_2 sorbent would have resulted in an estimated 4-lb saving in system weight.

The nonregenerable adsorption water removal system was chosen for the reliability potential of a "no moving part" concept. An adsorbent material was selected because of the desire to avoid a deliquescing material, and the attendant design problems. The Molecular Sieve 13X material was selected as the most efficient adsorbent at the expected operating temperature of approximately 125 to 150°F.

For thermal control during flight, both the evaporative water and radiant panel systems are used. For ground operation Freon is supplied to the evaporator of the water system, and during recovery, ambient air is circulated through the life cell.

Water was chosen as the evaporative coolant for flight because of its high latent heat of vaporization. The use of Freon during the pre-launch period, greatly simplifies the design of the ground cooling equipment.

The decision to develop the radiant panel system was based on its desirability for extended missions and increased heat loads where the weight and volume of water required would become excessive. Even for the missions being considered, the radiant panel system weighs less than the additional water which would be required to absorb the total heat load during orbit.

The ambient-air ventilation system is by far the simplest and lightest solution for thermal control during the recovery period.

The approaches selected to satisfy the various functions of the thermal and atmospheric control system are summarized in Table 3.

The system hardware*, which has already been described in general, is shown in Fig. 3. The system and its operation are described in some detail below.

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*Developed by the AiResearch Manufacturing Division of the Garrett Corp.

Table 3

SELECTED THERMAL AND ATMOSPHERIC CONTROL SYSTEM – BRAVO

Oxygen supply	High pressure gas (7500 psia)
Carbon dioxide removal	Lithium hydroxide
Water removal	Molecular Sieve 13X
Trace contaminant removal	Activated carbon
Temperature control	
Pre-launch	Evaporative (Freon)
Ascent and re-entry	Evaporative (water)
Orbit	Radiant panels
Recovery	Ambient air circulation, with heater

The oxygen is supplied to the life cell on demand from one of two high pressure reservoirs. The normal pressure reducers provide a regulator upstream pressure of 100 psia. If this pressure drops to 80 psia, the emergency pressure reducer opens to admit oxygen from the emergency reservoir. The regulator functions to maintain a nominal life cell pressure of 5 psia.

The life cell atmosphere is circulated in primary and secondary systems. The primary circulation system provides a relatively low flow for moisture, CO_2, and trace contaminant removal, and orbit temperature control. The secondary circulation system provides a higher flowrate which is required for ground, ascent, and re-entry cooling, and to provide the proper life cell gas velocity.

A centrifugal compressor provides circulation through the primary circulation system. A differential pressure switch, sensing compressor pressure rise, is provided to energize the spare compressor in the event of failure of the main compressor. A debris trap is located upstream of the compressors to collect any foreign material in the system.

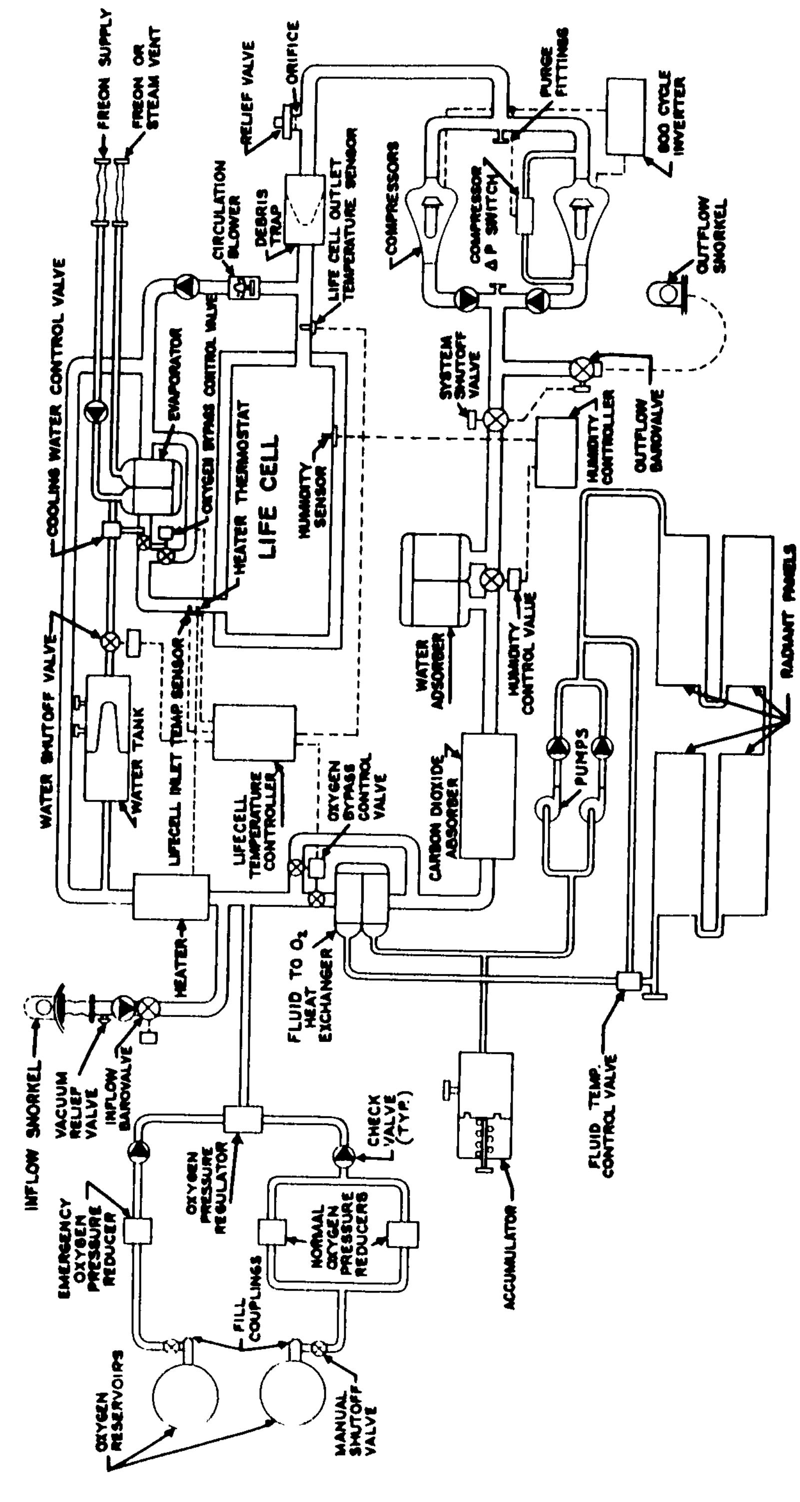

Fig. 3 Thermal and Atmospheric Control System – Bravo

The compressor discharges into the Molecular Sieve water adsorber. Oxygen is bypassed around the adsorber as required to maintain life cell relative humidity at the desired value. A humidity sensor mounted in the life cell controls the position of the bypass valve.

The gas then passes through the lithium hydroxide CO_2 absorber. This unit also contains the activated carbon and a dust filter.

The flow then enters the heat exchanger used for orbit cooling. The transport fluid (Fluorochemical 75*) is pumped through this heat exchanger and through the radiant panels. Two pumps are provided in parallel; however, either pump is capable of handling the full system load. Heat is thus transferred from the gas stream to the radiant panels, and then to space, through the recovery capsule walls. The flow control valve in the fluid circuit maintains a constant fluid temperature at the heat exchanger inlet. The average life cell temperature is controlled by positioning the heat exchanger gas bypass valve.

The oxygen flow is then directed through the heater and into the secondary circulation duct. A fan draws oxygen from the life cell and directs it to the evaporator inlet where it mixes with return gas from the primary circulation system. The combined flow then passes through the evaporator and into the life cell. During pre-launch operations, Freon is supplied to the evaporator from a ground source. During ascent and re-entry, water from the on-board tank is supplied to the evaporator. The water flowrate is controlled to provide a constant oxygen outlet temperature from the evaporator core. Average life cell temperature is controlled by the position of the oxygen bypass valve.

Prior to re-entry, the fan and fluid pumps are de-energized and the evaporator bypass is fully closed. The inflow barometric valve opens after parachute deployment, and a check valve prevents loss of life cell pressure. After the ambient and life cell pressures have equalized, the out flow barometric valve opens, and the system shutoff

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*Manufactured by the Minnesota Mining and Manufacturing Co.

valve closes. The compressor then draws ambient air through the inflow snorkel, the heater, and the life cell, and exhausts it through the outflow snorkel. The snorkel valves are provided to prevent water from entering the life cell circulation system during the ocean recovery period.

Figure 4 is a photograph of the life cell showing the location of the thermal and atmospheric control system, including the radiant panels. Two more radiant panels are mounted on the opposite side of the life cell.

BRAVO DEVELOPMENT PROBLEMS

Water Removal

The preliminary design studies indicated magnesium perchlorate $Mg(ClO_4)_2$ to be the most efficient sorbent of those considered. To obtain bed design information and evaluate magnesium perchlorate performance, a test of such a bed was performed. A magnesium perchlorate column was prepared and installed in a test fixture. Gas at the system design flowrate and relative humidity was introduced into the bed. Bed outlet dew point was monitored. The test was terminated prematurely when test instrumentation showed that the bed was not removing sufficient water vapor from the gas stream. Inspection of the bed following the test showed that the magnesium perchlorate had deliquesced.

An investigation of tests performed for WADD by the Eclipse-Pioneer Division of the Bendix Corp. indicated considerable difficulty in the design of a packed column to use magnesium perchlorate. They reported serious channeling and sludging, which was attributed to deliquescing of the material.

Considering the relatively short development time allocated for the completion of the design, it was decided to use a solid adsorbent material. The selection of Molecular Sieve 13X has already been described.

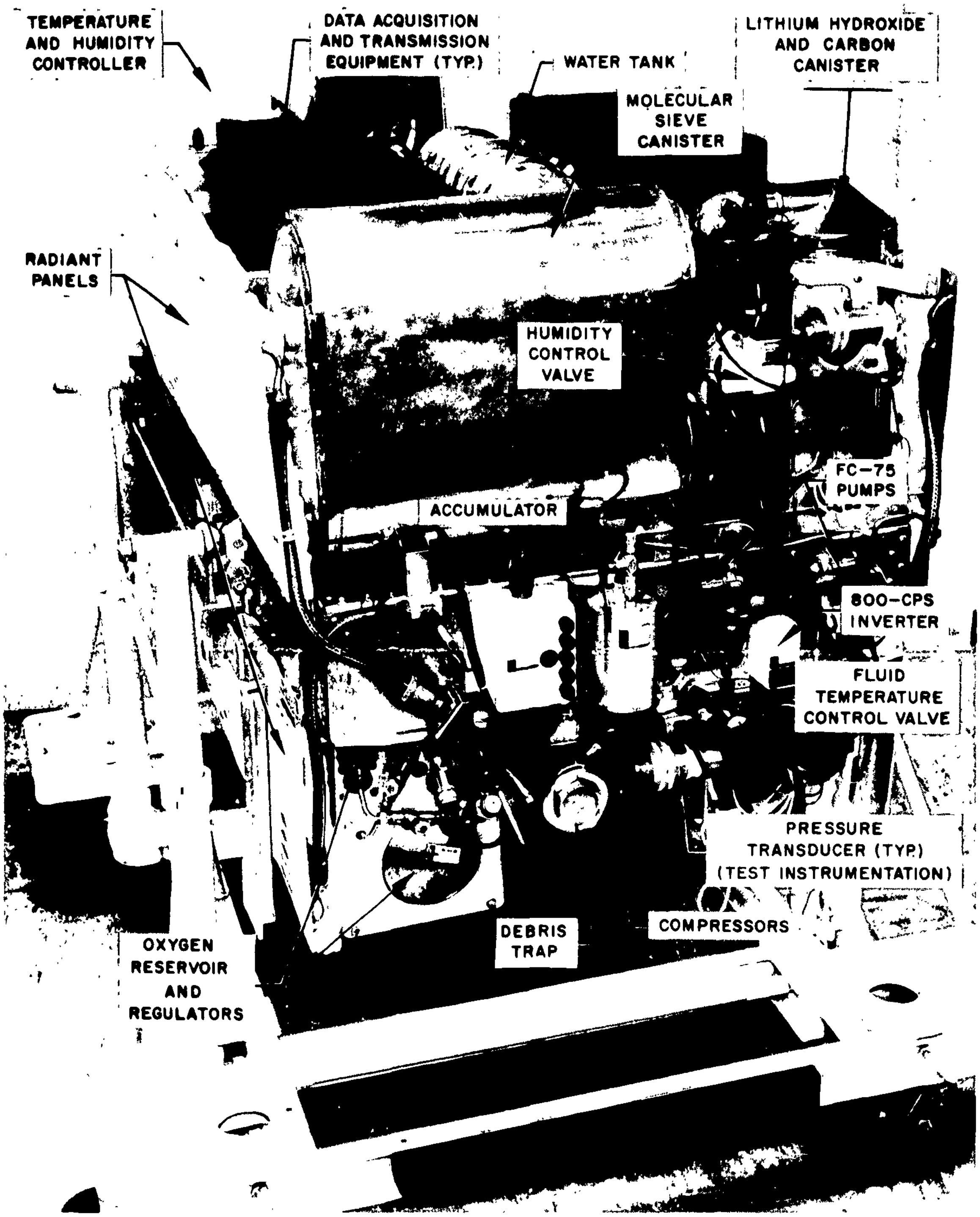


Fig. 4 Bravo System

A Molecular Sieve bed was designed, fabricated, and tested. The tests showed that with reasonable care in design of bed length, gas velocity, and sieve packing, bed outlet dew points below 0°F are readily obtainable. Results of this test are presented in Fig. 5.

Radiant Panel Transport Fluid

A glycol-water mixture was initially chosen as a transport fluid for the radiant panel cooling system because of the following favorable characteristics:

Low vapor pressure – allows for low system pressures in the expected -65 to 150°F temperature range.

High specific heat – allows for low system flow to minimize transport tube size and pump power.

Relatively high thermal conductivity – provides for higher film coefficients in the heat transfer equipment.

Relatively low freezing point – prevents freezing in the radiant panels at minimum load conditions.

The high viscosity at low temperature was not considered to be critical because very low flowrates were required.

A more rigorous thermal analysis of the radiant panel cooling system, completed subsequent to the selection of glycol-water as a transport fluid, indicated fluid temperatures of -80°F under minimum load conditions. Reduction of flow could be tolerated under minimum load, but freezing of the transport fluid in the radiant panels would result in loss of thermal control. A survey of available cooling fluids resulted in the selection of Fluorochemical 75 (FC-75) as a more desirable radiant panel cooling fluid. A comparison of an ethylene glycol-water solution and FC-75 is presented in Table 4. The vapor pressure of FC-75 compares favorably with glycol-water.

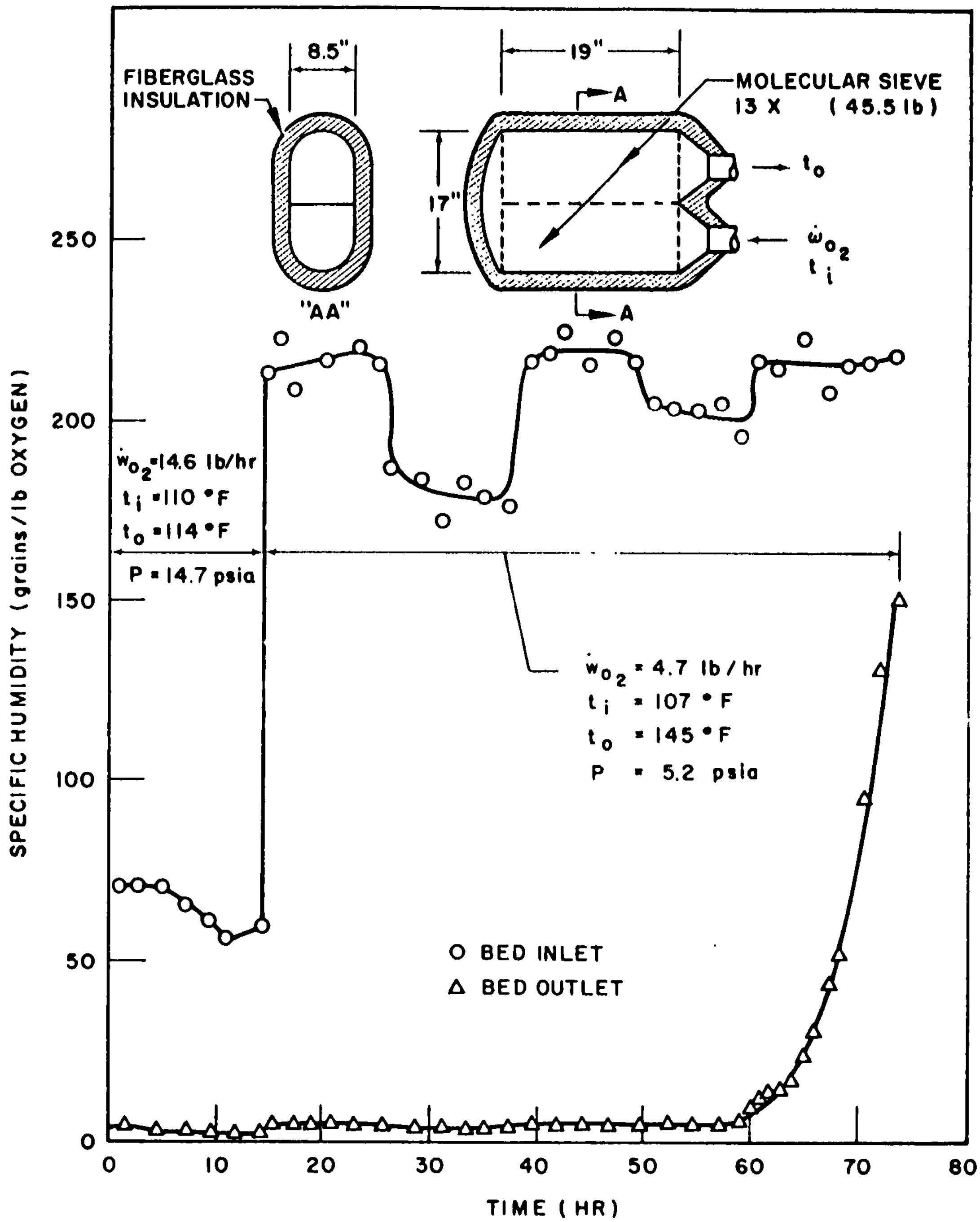


Fig. 5 Performance of H_2O Adsorber vs. Time in Bravo System

Table 4

COMPARISON OF ETHYLENE GLYCOL – WATER MIXTURE AND FLUOROCHEMICAL 75[a]

	62.5% Ethylene Glycol Water Solution	FC-75
Vapor pressure at 150°F (mm Hg) (maximum system temperature)	130	35
Freezing point (°F)	- 65[b]	-171
Viscosity - 50°F (centipoise)	≈ 550	9.90
0°F	34	3.74
150°F	1.7	0.72
Thermal conductivity at 75°F ($Btu/hr\text{-}ft^2\text{-}°F/ft$)	0.221	0.072
Specific heat at 75°F (Btu/lb-°F)	0.747	0.257
Specific gravity at 75°F	1.078	1.75
Ratio of film coefficients (h_{FC-75}/h_{Glycol})	0.34[c]	
Ratio of $\Delta p/L$ $\dfrac{(\Delta p/L)_{FC-75}}{(\Delta p/L)_{Glycol}}$	0.55[c]	

(a) Property values from <u>Heat Transfer Fluids for Aircraft Equipment Cooling Systems, WADC TR 54-66, Feb 1954</u>
(b) First crystals form.
(c) Fully developed laminar flow, inside a tube, at 75°F.

The lower specific heat of FC-75 is offset by a lower viscosity and higher density, resulting in lower system pressure drop for the same fluid thermal capacity $(\dot{W}C_p)$. The lower thermal conductivity of FC-75 results in a lower heat transfer coefficient, in laminar flow, for the same tube diameter and fluid thermal capacity $(\dot{W}C_p)$. The freezing point of FC-75 is considerably below the required design value. FC-75 is also a very stable compound in the expected temperature range of -80 to +150°F and has favorable radiation stability.

Carbon Dioxide Absorber

A full mission test was performed on the lithium hydroxide bed. Air at the design flowrate, temperature, and humidity, was forced through the bed in a closed cycle,

and carbon dioxide at the average expected metabolic rate was introduced into the air upstream of the lithium hydroxide bed. Bed inlet and outlet carbon dioxide partial pressures were measured. The test showed favorable inlet and outlet partial pressures until approximately 50 hr. Provisions for additional lithium hydroxide in the bed were made to extend bed life to the required 62 hr.

Two additional problems were encountered during the test. Pressure drop of the bed was greater than anticipated, primarily because of the relatively high resistance of the filters required to collect the lithium hydroxide dust generated during the recharging process. Also, rough handling of the lithium hydroxide during or after charging of the bed may break the LiOH grains, producing powder, which aggravates the pressure-drop problem. The effects of vehicle vibration and acceleration on bed packing must be given careful consideration.

COCOA SYSTEM DESIGN

Preliminary Design Studies

In the design of the Cocoa system, which is to be used for extended missions, conservation of weight, volume, and power has taken on considerably more importance.

During the preliminary design phase, several modifications of the Bravo system were investigated. The use of a condensation-separation water removal method provides a considerable weight saving when compared with a nonregenerable water adsorber. Close control over humidity, however, requires a controllable reheating capability with the condensation-separation approach. In the interest of simplicity, the life cell humidity requirements were reviewed. It was concluded that the range of 40 to 60%, used in the Bravo system to eliminate any environmental stress on the animal during test, could be relaxed without seriously affecting the results of anticipated flight experiments. The expected humidity excursions with a simple condensation-separation system are discussed later.

The use of a 14.7-psia cabin pressure results in a significant reduction in blower power, over that for a 5-psia system, for a given mass flow through the system, and the reduction in volumetric flow at 14.7 psia was determined not to be a problem. The use of a 14.7-psia air atmosphere requires the addition of diluent supply reservoirs and flow regulators, increases the leakage mass rate for a given leak area, and requires an oxygen partial pressure control system. Calculations of the net reduction in power and the increase in weight for equipment and leakage, indicated a significant saving with the higher pressure system. Considerable effort is being expended to minimize the pressure drop of individual components to minimize the required fan power.

The space radiator has been placed so that it views space directly rather than through the capsule walls as was the case with the Bravo system. In addition, it was found desirable to more completely thermally isolate the life cell and environmental control system equipment from the recovery capsule. This makes the external load on the life cell and associated equipment less sensitive to changes in launch time and orbit geometry.

System Description

A schematic diagram of the Cocoa system which evolved from these investigations is shown in Fig. 6.

Gas supply and pressure control. The life cell is provided an oxygen-nitrogen atmosphere at a total pressure of approximately 14.7 psia from a gaseous supply system consisting of two separate O_2 sources and two separate N_2 sources. The O_2 system consists of identical high-pressure (7500 psia) tanks which are divided into primary and secondary supplies. The secondary supply will normally be used during the later portion of the mission, and as an emergency supply. It remains inoperative until the primary system delivery pressure falls to approximately 80 psia. The N_2 system also consists of high-pressure tanks which are similarly divided into primary and secondary supplies. The secondary regulator remains closed until the life cell pressure falls to approximately 14.2 psia, from the primary regulator setting of 14.7 psia.

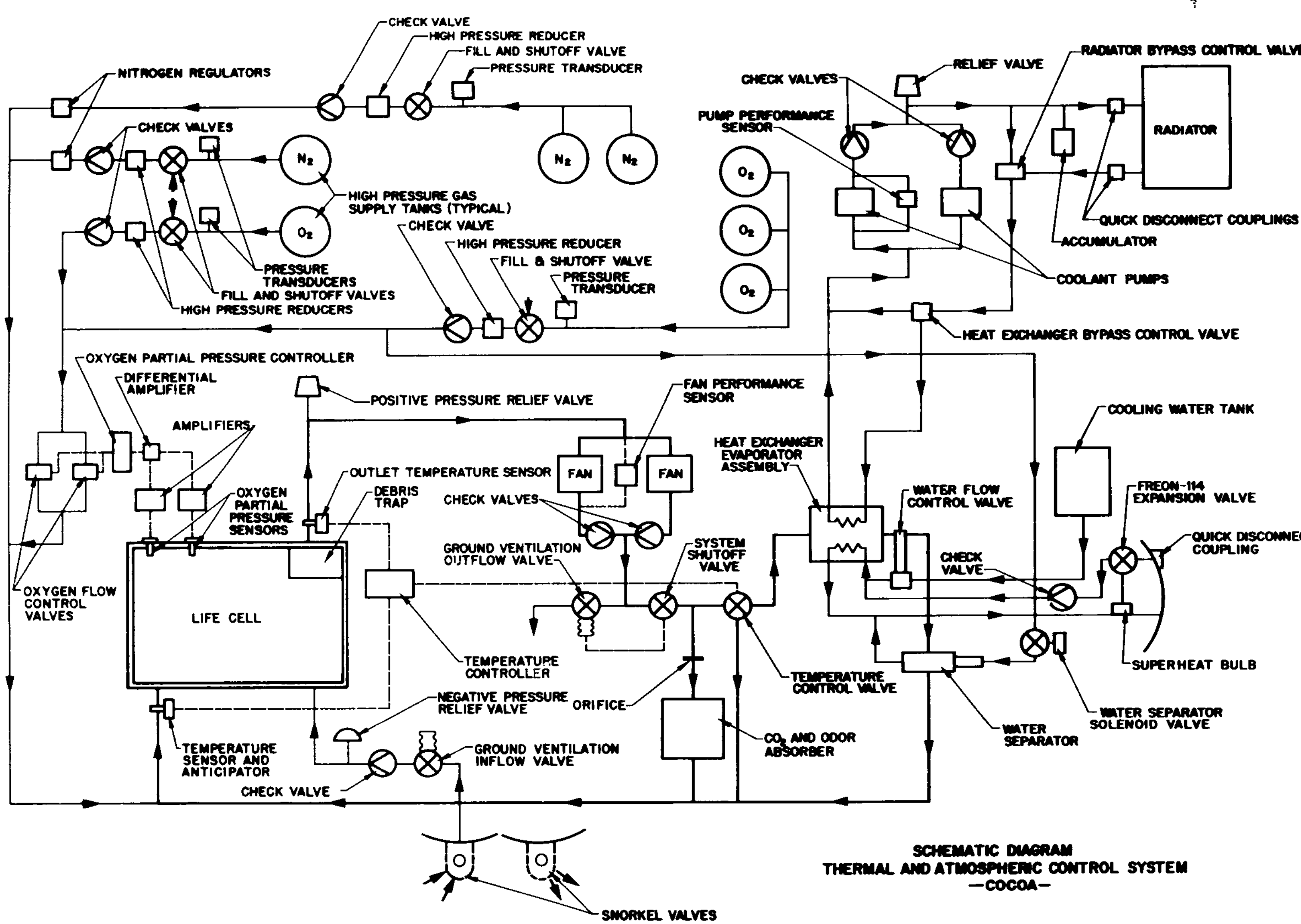


Fig. 6 Environmental Control System – Cocoa

The oxygen partial pressure control system operates to maintain the partial pressure of oxygen in the life cell at a nominal value of 3.1 psia. Redundancy is incorporated in this extremely vital system. Two sensor units provide signals to separate amplifiers. A differential amplifier provides the controller with the higher of the two voltages generated by the two pO_2 amplifiers.

A vacuum relief valve is provided in the ground ventilation inlet duct to prevent ambient pressure from exceeding life cell pressure by more than 0.5 psi. A pressure relief valve is provided to relieve life cell pressure at approximately 16 psig.

Carbon dioxide and trace gas removal. Carbon dioxide and trace contaminants are removed in the same manner as they were in the Bravo system. The only change is in the physical size of the unit and its location in the system. Approximately one-third of the total flow passes through the LiOH bed, which is more than sufficient to remove the required amount of CO_2 and to keep the level in the life cell below 4 mm Hg partial pressure.

Water removal system. Moisture is condensed from the circulating atmosphere in the heat exchanger-evaporator and is removed in a sponge-type water separator. The sponge is compressed periodically by pneumatic power obtained from high-pressure O_2, to discharge the entrapped water. No provision has been made to retrieve the water and it is discharged overboard.

Thermal control system. The method used for rejecting heat from the system depends upon the operating phase. The life cell atmosphere is cooled and dehumidified continuously in the heat exchanger. The coolant can be either a ground Freon supply, an on-board water supply, or FC-75 circulating between the radiator and the heat exchanger. The temperature controller responds to signals from life cell inlet and outlet temperature sensors and controls the amount of air bypassed around the heat exchanger-evaporator. The water flow control valve is a self-contained thermostatic valve which operates to control the flow of water so that a nominal 60°F air temperature is maintained at the

outlet from the evaporator. The FC-75 heat exchanger bypass flow control valve is of similar construction and operates to maintain a fluid inlet temperature to the heat exchanger less than approximately 50°F. Another FC-75 flow control valve bypasses the radiator to maintain the inlet temperature to the heat exchanger at approximately 35°F. The interaction of these controls automatically changes the mode of operation from the evaporative mode during ascent to the radiator mode during orbit, and back to the evaporative mode if the radiator performance degrades to where it can no longer reject the required amount of heat.

For circulation of the atmosphere, two fans are provided in parallel; however, only one fan is normally operated. The standby fan is automatically started in the event of a failure of the normally operating fan.

Barometrically operated ventilation valves in the system operate during descent to allow circulation of ambient air through the air cell. The inflow valve opens at approximately 9.2 psia and the outflow valve opens at 13.2 psia. Simultaneously with the opening of the outflow valve, the system shutoff valve closes. Between the opening of the two valves, the life cell is depressurized at a controlled rate to the ambient pressure level.

Two pumps are provided in parallel to circulate FC-75; however, only one pump operates at a time.

With the system just described, the humidity in the life cell is a function of the animal activity level and the life cell heat loads. This variation is shown as a function of life cell heat load for maximum and minimum animal activity levels in Fig. 7. Typical maximum and minimum life cell heat loads are indicated on the curve to illustrate the variation of relative humidity expected for this system.

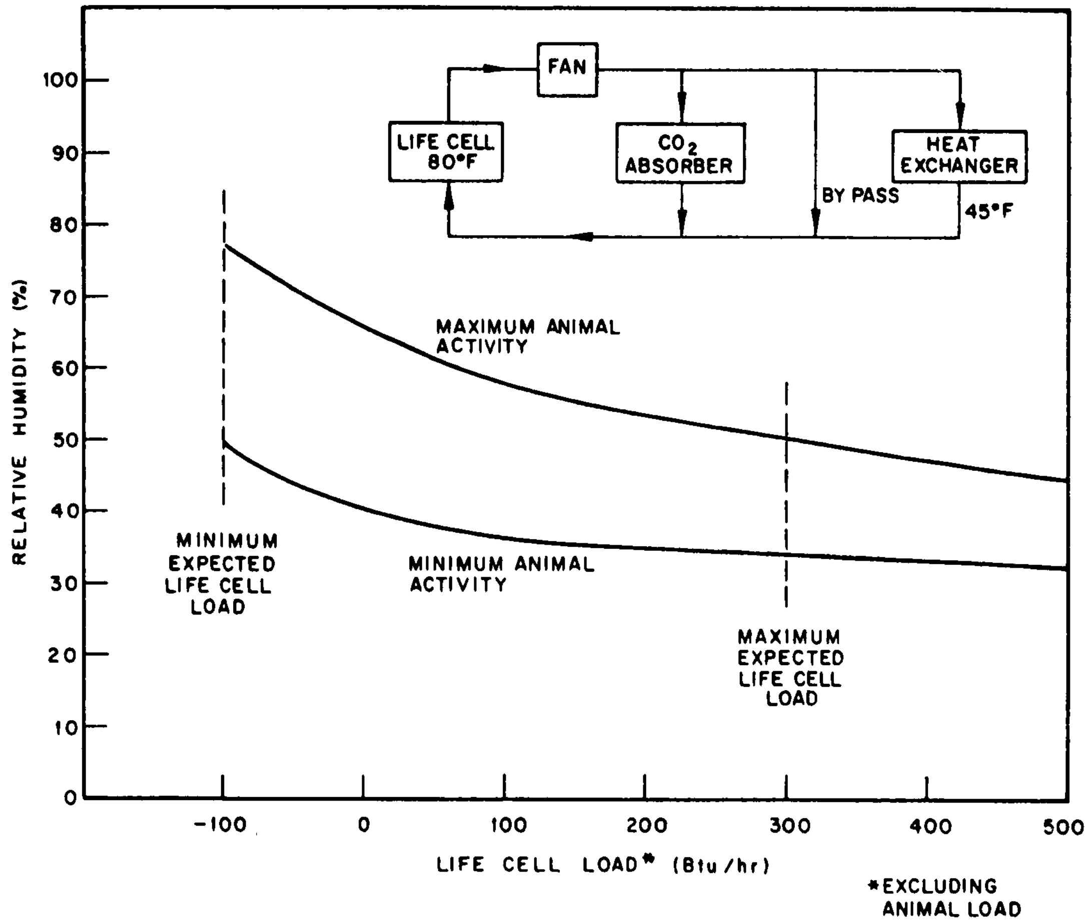


Fig. 7 Relative Humidity vs. Life Cell Heat Load for the Cocoa System

MANNED SYSTEM STUDIES

Manned Versus Animal Systems

In addition to the animal capsule development work described, LMSC has been engaged in extensive studies related to multimanned missions of extended duration. From a technical point of view, it is no more difficult to sustain a human subject in a closed environment than it is to sustain a chimpanzee. In one respect, it is more difficult with the

animal because he does not understand the implications of his own actions, and the supporting systems must take this into account. On the other hand, the probability of mission success must be extremely great when a human subject is involved, and more emphasis must be placed on emergency provisions such as the detection and control of hazardous situations, i.e., decompression, fire, etc. One advantage with a manned system is the crew's ability to monitor vehicle and system performance, and take corrective action as required.

Metabolic loads differ greatly between the man and the chimpanzee. A typical astronaut will have a basal metabolic rate (BMR) of approximately 1740 Kcal/day, while the 50-lb chimpanzee has a BMR of approximately 800 Kcal/day. Total metabolism will vary even more. The animal is restrained to prevent him from reaching critical items of equipment and to simplify the waste collection problem. As a result, his total work output is restricted. It is quite possible that spacecraft crews will exercise to maintain muscle tone, presuming that they do not get sufficient exercise by operating and maintaining the vehicle.

Open Versus Closed Systems

The animal systems which LMSC has been developing are strictly "open," i.e., they are not designed to reclaim materials such as water and oxygen from the metabolic outputs. This type of system is quite satisfactory even for multimanned missions of several weeks' duration. Looking ahead, however, to multimanned missions of durations exceeding 20 to 30 days, it can be shown that there is a significant weight saving achieved by starting to "close" the ecological cycle, even though this involves more equipment and more power.

The Metabolic Balance

The design of a closed system requires that the balance between metabolic input and output be examined rather carefully. When this is done, it becomes apparent that a

perfect closure of the system is impossible because of the inevitable cabin leakage and because of regeneration inefficiencies. Undoubtedly, the process is not perfectly balanced here on earth, but the imbalance becomes more significant as it approaches a larger proportion of the total material present.

In examining the metabolic balance, one must start with the BMR, which is proportional to body surface area (Ref. 14). The constant of proportionality varies with sex and age (Ref. 15). For a 35-yr old male, 5 ft 9 in. in height, and weighing 154 lb, the BMR is approximately 1740 Kcal/day or 290 Btu/hr.

The total energy expenditure is difficult to ascertain with accuracy. However, an estimate can be made by using Table 5, which is based on data from Refs. 3, 16, and 17.

Table 5

ESTIMATED SENSIBLE AND LATENT HEAT LOSSES AS A FUNCTION OF ACTIVITY

Activity	Sensible Heat Loss (Btu/hr)	Latent Heat Loss (Btu/hr)	Total Heat Loss (Btu/hr)
Sleep	240	60	300[a]
Rest, sitting	240	160	400
Light work	280	280	560
Medium work	320	640	960

(a) The heat dissipation for sleep was taken to be slightly above basal. Although during sleep, after rest, metabolism equals about 90% of basal, sleep, immediately after work, may involve a rate as high as 140% of basal.

For a typical work-rest cycle, it is not unreasonable to expect a total energy expenditure in the range of 2000 to 3000 Kcal/day, which will show up as approximately equal sensible and latent heat loads on the system. Over a period of time the energy expenditure must be offset by food intake, providing there is no gain or loss in body weight.

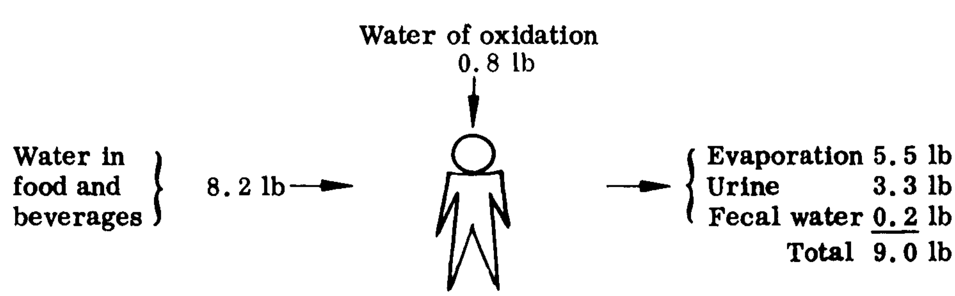
Each of the main types of foodstuffs furnishes a different amount of energy per gram oxidized, requires a different amount of oxygen per gram for its oxidation, and gives off different amounts of carbon dioxide and water per gram oxidized. Table 6 shows the interrelationship of these variables (Ref. 18).

Table 6

CONSUMPTION OF O_2 AND PRODUCTION OF CO_2 AND HEAT IN THE METABOLISM OF COMMON FOODSTUFFS

Substance	Oxygen to Oxidize 1 gm (cc)	Produced in the Oxidation of 1 gm		Respiratory Quotient
		CO_2 (cc)	Heat (Kcal)	
Starch	829.3	829.3	4.20	1.00
Glucose	746.2	746.2	3.74	1.00
Animal Fat	2013.2	1431.1	9.50	0.71
Protein	956.9	773.8	4.40	0.81

Once again, there must be a balance of water intake and output, adjusted for the water produced in the oxidation of foodstuff and for gains or losses in body water content. Water leaves the body through evaporation from the surfaces of the skin and lungs, as well as in urine and feces. A water balance based on a daily energy expenditure of 3060 Kcal and a diet of 77% carbohydrate, 12% fat, and 11% protein is shown below:



The evaporative loss is quite dependent upon the type of activity and the temperature and humidity conditions in the cabin. The amount of water in the food can vary considerably, depending upon the degree to which it is dehydrated. As a result of these variables, direct water intake can vary considerably.

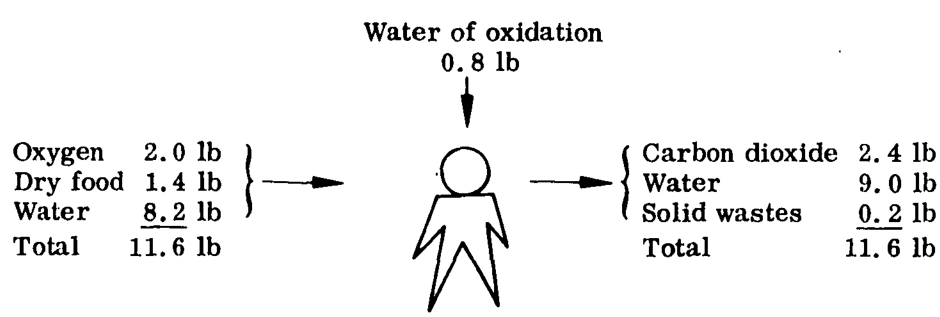
The water of oxidation is a function of the type and amount of foodstuff oxidized as shown in Table 7.

Table 7

WATER OF OXIDATION OF FOODSTUFFS

Substance	Water Produced per gm of Food Oxidized (gm)
Carbohydrate	0.55
Fat	1.07
Protein	0.41

A daily mass balance based on the same energy expenditure and diet used in the water balance appears below.



The Nearly Closed System

Both the purely chemical and the biological regeneration systems are under investigation at LMSC. One of the attractive points of the biological system is the possibility

of getting food as well as water and oxygen from the metabolic wastes, although normal food acceptability standards may be difficult to achieve.

Chemical regeneration appears to be a practical and extremely useful interim solution to the reclamation problem. With such a system, carbon dioxide is collected from the airstream by a suitable means and is reacted with hydrogen to form carbon and water. Water is condensed from the cabin atmosphere and requires only filtration to make it suitable for consumption. After distillation and filtration, water from the urine should be potable, although continued ingestion and reclamation of such water could present a problem due to buildup of trace impurities. No attempt is made to reclaim water from the feces.

Only a small portion of the water recovered from urine is ingested. The major portion of this water is electrolyzed to provide oxygen for breathing and leakage, as well as to provide hydrogen for the reduction of carbon dioxide. It turns out that the only system inputs required are food containing some water, and atmospheric diluent (if one is provided). A daily mass balance for such a system is presented in Fig. 8, based on the following assumptions:

Cabin total pressure	415 mm Hg
N_2 partial pressure	238 mm Hg
O_2 partial pressure	160 mm Hg
CO_2 partial pressure	4 mm Hg
H_2O partial pressure	13 mm Hg
Cabin leakage	0.52 lb/man-day
Crew energy expenditure	3060 Kcal/man-day
Diet	
Carbohydrate	77% (wt)
Fat	12% (wt)
Protein	11% (wt)
Ratio of sensible-to-latent heat	1.1
Efficiencies	
Urine water recovery	90%
CO_2 reduction	100%
Water vapor recovery	98%

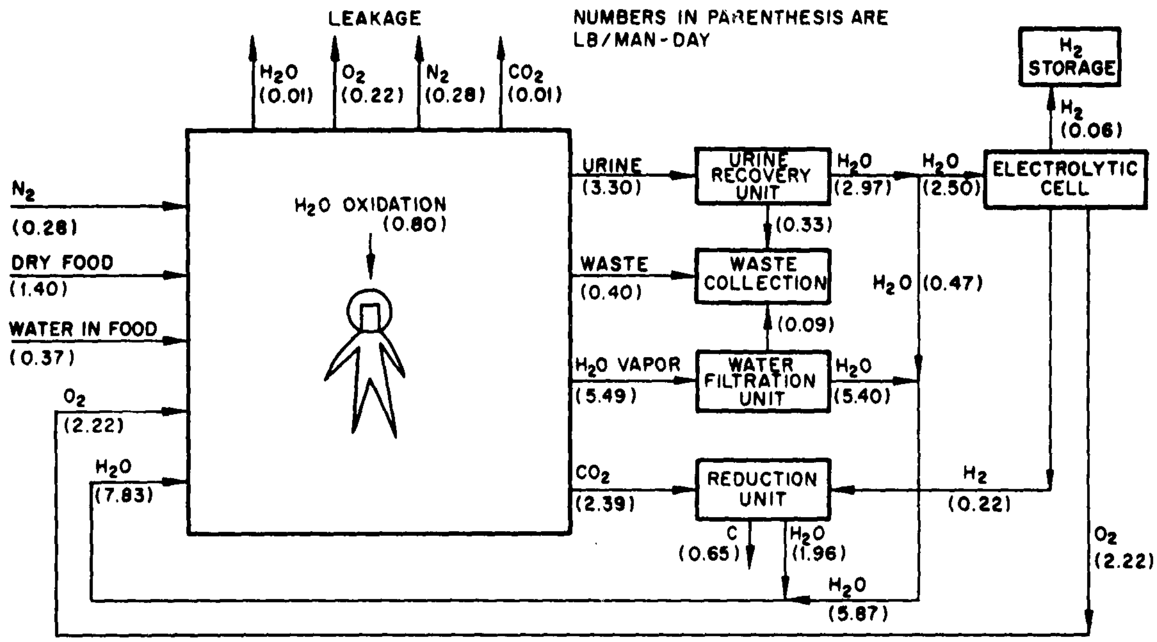


Fig. 8 Typical Mass Balance for the Nearly Closed System

Under the above conditions, a total of 2.05 lb/man-day of nitrogen, food, and water must be supplied. This compares with 12.1 lb/man-day of nitrogen, food, water, and oxygen had there been no regeneration whatsoever.

The mass balance is affected by all of the assumptions listed. As an example, the effect of varying cabin leakage and crew activity is demonstrated in Table 8. The design of a system to carry out the processes previously described does not appear to hinge upon any technological breakthroughs. It will require considerable engineering development, and other effort to establish the physiologic compatibility of the crew-system combination. In view of the substantial logistic payoff to be realized, however, such a development effort appears to be economically warranted.

Table 8

MATERIAL SUPPLY RATES AS A FUNCTION OF CABIN LEAKAGE AND CREW ACTIVITY

Cabin Leakage (lb/man-day)	Crew Activity (Kcal/man-day)	Material Supply Rate (lb/man-day)			
		N_2	H_2O	Dry Food	Total
0.52	3060	0.28	0.37	1.40	2.05
1.04	3060	0.56	0.63	1.40	2.59
1.04	1530	0.56	0.76	0.70	2.02

The design of a system to carry out the processes previously described does not appear to hinge upon any technological breakthroughs. It will require considerable engineering development, and other efforts to establish the physiologic compatibility of the crew-system combination. In view of the substantial logistic payoff to be realized, however, such a development effort appears to be economically warranted.

CONCLUDING REMARKS

The design of a thermal and atmospheric control system must reflect consideration of the following major items:

- Metabolic inputs and outputs associated with the occupants
- Effects on the occupants of the artificial atmosphere being provided
- Power dissipation of equipment and lighting
- Products of reaction of chemical processes in the system
- External environment of the vehicle

The analytical tools presently available for system analysis are adequate, but some effort to improve the accuracy of various analytical models, and the efficiency of numerical analysis techniques, would reduce the cost and time involved in system design.

The state of the art in open systems (those which do not reclaim materials such as oxygen and water from the metabolic outputs) is reasonably well advanced, and the open-system designer can devote more effort to improving reliability, simplifying component design, reducing power, and generally optimizing the design.

For extended multimanned missions it becomes extremely desirable to reclaim oxygen and water from the metabolic outputs. The nearly closed system, using strictly physical and chemical processes, rather than biological processes, to achieve the desired reclamation, appears to be a logical extension of the state of the art.

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